SSC DETECTOR SOLENOID DESIGN NOTE #33

TITLE: A Design of a Small Thin Superconducting Solenoid for a General Purpose 4π Detector at the SSC (Draft)

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1. Why thin small solenoid ?

A general purpose 4π detector is thought to be best for exploring the unknown energy regions that can be reached by the proposed Superconducting Super Collider (SSC). Among others, a detector with superior tracking devices with magnetic field is expected to be quite powerful in discriminating genuine events among formidable backgrounds that are present in high energy pp collisions. For example, the detection power of high p_t muons and isolated electrons could be enhanced substantially with a measurement of particle momentum.

The design of the present 4π magnetic detector is based on the Large Solenoid Detector proposed at the Berkeley workshop in 1987[1], except for one important point, the location of the superconducting solenoid. The large solenoid might be too large to be a realistic component of the detector. Though the large solenoid can be built with a reasonable extrapolation of the existing technology, its construction is rather non-trivial taking more than five years[2] and its diameter of 9.5m might preclude its fabrication at an off-site facility due to severe transportation issues[3]. In the large solenoid design, the supporting mechanism including installation of the entire calorimeter (~3000tons) inside the magnet cryostat will be a major engineering challenge. Consequently, the large solenoid plus calorimeter support could be potentially a major burden of the total detector cost. We think it is not worthless at this time to explore some other possibilities before proceeding to design the details of the detector.

The main motivation of the large solenoid was to maintain good hermeticity by locating the entire central and endcap calorimeters inside the solenoid. Ideally this is still true, but practically one has to take into account that the presence of other structural supports, cables and cryostats by themselves give rise to deviations from ideal hermeticity. Therefore, by making the inner solenoid thin [4], we believe effects of the small solenoid to hermeticity and energy measurement can be made relatively small. For instance, if the thickness of the magnet is less than $1X_0$, one can anticipate almost no effects in the energy measurements at the barrel region. This has been well demonstrated by existing detectors, such as CDF. Besides, in our configuration, the endcap calorimeter starts at the end of the solenoid for better hermeticity. This configuration, which is different from CDF, OPAL, TOPAZ and VENUS, avoids the presence of inert material in the middle of EM shower development. The return yokes locate at a distance from the end of solenoid, thus the solenoid is a floating type like that of ZEUS[5]. The magnetic field at the inner tracking part is not uniform as a consequence.

Recent progress in thin superconducting magnet technology and construction/operation experiences cumulated at various colliders made it very practical to proceed a realistic design of solenoid that is thinner than any of existing detector magnets. As for fabrication, three years seem to be enough for construction of the small superconducting magnet, and therefore plenty of lead time will be available for design and R&D coils. Indeed, it might be a good idea to construct a scaled prototype magnet in order to fully study the quench propagation as well as protection/detection schemes.

Fig.1 shows overall configuration of the proposed detector[6]. In this paper, we describe a preliminary design of thin solenoids with diameter of 3 m for the central field of 1.5T~2.5T.

2. General formulae of coil thickness (Transparency)

Using recent experinence with the three superconducting solenoids for TRISTAN experiments, i.e. TOPAZ, VENUS and AMY, we can estimate how thin a superconducting coil can be made using existing technology. There is a good summary of conventional field strength superconducting solenoids ($B<2T$) [7,8]. Here we extrapolate to magnets designs for higher field($B\geq 2T$).

For a thin magnet, the coil and cryostat thickness, t_{mag} can be split into two parts, namely an aluminum-equivalent part and a copper-equivalent part:

$$t_{mag} = t_{Al} + t_{Cu}.$$

The quantities t_{mag} and t_{Cu} are further divided as:

$$t_{Al} \approx t_{IV}(r) + t_{RS}(r) + t_{ST}(r,B^2) + t_{OV}(r)$$

and

$$t_{Cu} \approx tsc(B),$$

in which IV, RS, ST, OV and SC represent the inner vessel, radiation shield, aluminum stabilizer, outer vessel and superconducting wire, respectively, while r is the magnet radius and B it the magnetic field. We evaluating each term as follws, where r is in [meters], B is in [Tesla] ;

IV : the inner wall of the vacuum vessel

$$t_{IV}(r) = P\frac{r}{\sigma} = 10^4\ \mathrm{kgf/m^2} \cdot \frac{r}{5\times10^6\mathrm{kgf/m^2}} = 2\times10^{-3}r\ ,$$

RS : the radiation shield

$$t_{RS}(r) = \eta_{RS}\frac{1}{K}\cdot 2\pi r = 2\times\frac{r}{1\times10^{-3}}$$

which is estimated from the case for TOPAZ.

ST : stabilizer including support structure against the magnetic pressure

$$t_{ST}(r,B^2) = \frac{1}{\rho_{Al}}\cdot\frac{1}{\int c\,d\theta}\cdot\frac{1}{2\pi r}\cdot\frac{B^2}{2\mu_0}\pi r^2$$

$$= \frac{1}{2.7\times10^3\ \mathrm{kg/m^3}}\cdot\frac{1}{10^4\ \mathrm{J/kg}}\cdot\frac{B^2}{4\times4\pi\times10^{-7}}\cdot r$$

$$= 7.4\times10^{-3}\cdot B^2\cdot r\ ,$$

from the relation of " heat capacity = stored energy." We assume that the temperature rise of the coil is 80°K at a quench.

OV : the outer wall of vacuum vessel

$$t_{OV}(r) = \eta_{OV}\cdot r = 1\times10^{-2}\,r$$

obtained from the relation

$$P_c = \xi\cdot\frac{E}{(\frac{r}{t})^{2.5}\cdot\frac{l_z}{r}} = 1.6\ \mathrm{atm}$$

for the maximum sustainable pressure in the outer shell made of aluminum alloy. If newly developed Al-honeycomb structure is used, we can reduce the equivalent thickness by a factor of 3, i.e. $t=0.33\times10^{-2}r$.

SC : superconducting wire NbTi/Cu(1:0.8) with operational current density of

$$J_{SCM}(\mathrm{operation}) \approx 0.6\cdot\frac{k}{B_{op}/B_{ref}} = \frac{4.2\times10^9}{B_{op}[\mathrm{Tesla}]}\ \mathrm{A/m^2}$$

deduced from Jc(NbTi)=2.5×10^9 A/m^2 at 5 Tesla and 4.2°K for the SSC accelerator wires, where the factor 0.6 is for safety margin.

$$t_{sc} = \frac{B^2}{\mu_0 k}\cdot\frac{1}{\cos\theta} = \frac{B^2}{4\pi\times10^{-7}\times4.2\times10^9}\cdot\frac{1}{\cos\theta}\ [\mathrm{m}]$$

where θ is the polar angle to the edge of the coil and the cosθ term takes into account the effect of finite magnet length;

$$B_{center} = \mu_0 I[\mathrm{Amp/m}]\cdot\cos\theta = \mu_0 tJ\cos\theta.$$

By summing all these terms, one gets

$$t_{AL} = 2\times10^{-3}r + 2\times10^{-3}r + 7.4\times10^{-3}B^2r + 10^{-2}r,$$

and

$$t_{SC} = 1.8\times10^{-4}\cdot\frac{B^2}{\cos\theta}.$$

Total radiation and interaction thickness are given by

$$t_{radiation} = (0.16 + 0.083\cdot B^2)\cdot r + 0.012\frac{B^2}{\cos\theta} \quad X_0$$

$$t_{interaction} = (0.036 + 0.019\cdot B^2)\cdot r + 0.0011\frac{B^2}{\cos\theta} \quad \lambda_0$$

It should be noted that, in the present estimate, we assumed the ratio of stored energy to cold mass, E/M, to be 10 Joules/gram, the value proven by a prototype solenoid for ASTROMAG[9]. Fig.2 shows the total radiation and collision lengths as a function of coil radius. It is obvious from the figure that the B^2 term for stabilizer dominates at higher magnetic field.

From the figure, it is clear that we can achieve radiation thickness of less that $1X_0$ and collision length of less than $0.2\lambda_0$ for a coil diameter of around 3m with central field of 2 Tesla.

3. Priciple design of superconducting solenoid with coil radius of 1.5m

We here present a principle design of thin superconducting solenoid with coil radius of 1.6m for the central magnetic field of 1.5T to 2.5T. The present design is based on the construction as well as operation experiences of thin superconducting solenoids for CDF, VENUS and TOPAZ[8]. In addition, as stated above, it becomes rather convincing that one is able to raise the limit of the ratio of stored energy to coldmass, which is a critical parameter for protection of magnet at the time of quench, by a factor of 2 through the recent R&D work[9].

One of new ideas adopted in the present design is to enhance substantially the transverse speed of quench propagation with the use of thin axial liners made of pure aluminum that are attached to inner edges of wound superconducting cables[9]`. The enhancement of the transversed quench velocity enables the stored energy to be uniformly dumped in the coil and therefore supresses the maximum temperature rise in the coil.

A recent R&D work also made it possible to use Al-honeycomb structure for the outer wall of cryostat[10,11]. This will help in reducing material of the magnet.

Fig.3 illustrates the cross section of the solenoid. It is necessary to occupy a radial space of 25cm. Table 1 lists the overall dimensions assumed in the present design.We summarize the main parameters of the solenoid in Table 2 for three cases, 1.5T, 2.0T and 2.5T. Table 3 shows parameters for superconducting cables, while Table 4 gives details of the transparencies in terms of radiation and interaction length[12]. Fig.4 shows the profile of magnetic field. In the present calculation, we have assumed no return yokes for simplicity.

4. Summary

We propose a thin superconducting solenoid for a general purpose 4π detector for the SSC. The overall detector design is based on the conceptual design of the Large Solenoid Detector except for the location of magnet. Based on the recent developments on superconducting magnet technology, general formulae are presented for radiation and interaction thickness. A principle design of a thin solenoid is presented for the case of coil radius of 1.6m and 8m in length with the central field of 1.5T, 2T and 2.5T.

In conclusion, it seems to be quite practical to construct a thin superconducting solenoid with total thickness of less than $1X_0$ and $0.2\lambda_0$ at B=2T for coil radius of 1.6m

Acknowledgement

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[6] K.Ogawa, presented at the Shinshu Workshop on the hadron collider physics, August, 1988 and at the SSC study seminar at KEK, September, 1988.

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[9] A.Yamamoto et al., IEEE Transactions on Magnetics, 24(1988)1421.

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[11] Y.Makita et al., presented at the Informal Meeting on Balloon-borne Experiments, KEK, Feb.14, 1989.

[12] We used following parameters in calculation of radiation and interaction thickness:

	X_0	λ_0
aluminum	89 mm	394 mm
high strength Al alloy	81 mm	380 mm
copper	14.3 mm	151 mm
superconductor	16 mm	174 mm
GFRP	190 mm	530 mm
(CFRP	240 mm	550 mm)

Figure captions

Fig.1 Cross sections of the proposed small solenoid detector.

Fig.2 Coil transparencies as a function of solenoid radius. Dottted lines are for the cases using Al-honeycomb structure for the outer pressure vessel.

Fig.3 Cross section of the thin superconducting solenoid.

Fig.4 Flux density (a) and field strength (b) of the 2 T solenoid,assuming no return yokes present.

Table 1. Dimension of Cryostat and Solenoid

Cryostat	Inner Radius	1500 mm
	Outer Radius	1750 mm
	Length	8000 mm
Solenoid	Average Radius	1600 mm
	Length	7700 mm

Table 2. Main Parameters of the Coil

Central Field $B_{max}(Z=0)$	1.5	2.0	2.5	Tesla
$(NI)_{max}$	10.0	13.3	16.6	MAt
Nominal operating current	10000	10000	10000	A
Stored energy	55	99	154	MJ
Stored Energy/effective cold mass	10	10	10	KJ/Kg
Self inductance	1.1	2.0	3.1	H
Magnetic pressure (average)	0.9	1.6	2.5	MPa
Transparency				
radiation length	0.49	0.76	1.12	X_0
interaction length	0.11	0.17	0.24	λ_0

Table 3. Parameters of the Superconducting Cables at B = 2 Tesla

Material		NbTi/Cu/Al
		0.55 : 0.45 : 32
Dimensions	overall	5.6×35 mm^2
	NbTi/Cu matrix	2×3 mm^2
Operating current		10,000 A
Operating current density		
in NbTi		3000 A/mm^2
in NbTi/Cu matrix		1667 A/mm^2
Load line ratio (I_{op}/I_c) at 5°K		~ 80%
Insulation material		Kapton/Glass
lamination		
Turn to turn thickness		0.2 mm

Table 4. Transparency of the magnet

magnetic field	1.5 T			2.0 T			2.5 T		
element	t	X_0	λ_0	t	X_0	λ_0	t	X_0	λ_0
Outer vessel (Al-Honycmb)	6	0.067	0.0152	6	0.067	0.0152	6	0.067	0.0152
Outer radiation shield(Al)	1	0.011	0.0025	1	0.011	0.0025	1	0.011	0.0025
Support shell (Al-alloy)	7.0	0.086	0.0184	12.3	0.152	0.0324	19.3	0.238	0.0508
Conductor (Al stabilizer)	19.1	0.215	0.0485	34.2	0.384	0.0868	52.7	0.592	0.1338
(S.C. matrix)	0.4	0.025	0.0023	1.03	0.064	0.0059	2.0	0.125	0.0115
(GFRP insulation)	2	0.010	0.0038	2	0.010	0.0038	2	0.010	0.0038
Inner radiation shield(Al)	1	0.011	0.0025	1	0.011	0.0025	1	0.011	0.0025
Inner vacuum vessel (Al)	4	0.045	0.0101	4	0.045	0.0101	4	0.045	0.0101
Miscellaneous		0.020	0.0075		0.020	0.0076		0.020	0.0076
Total		0.490	0.111		0.764	0.167		1.119	0.2378

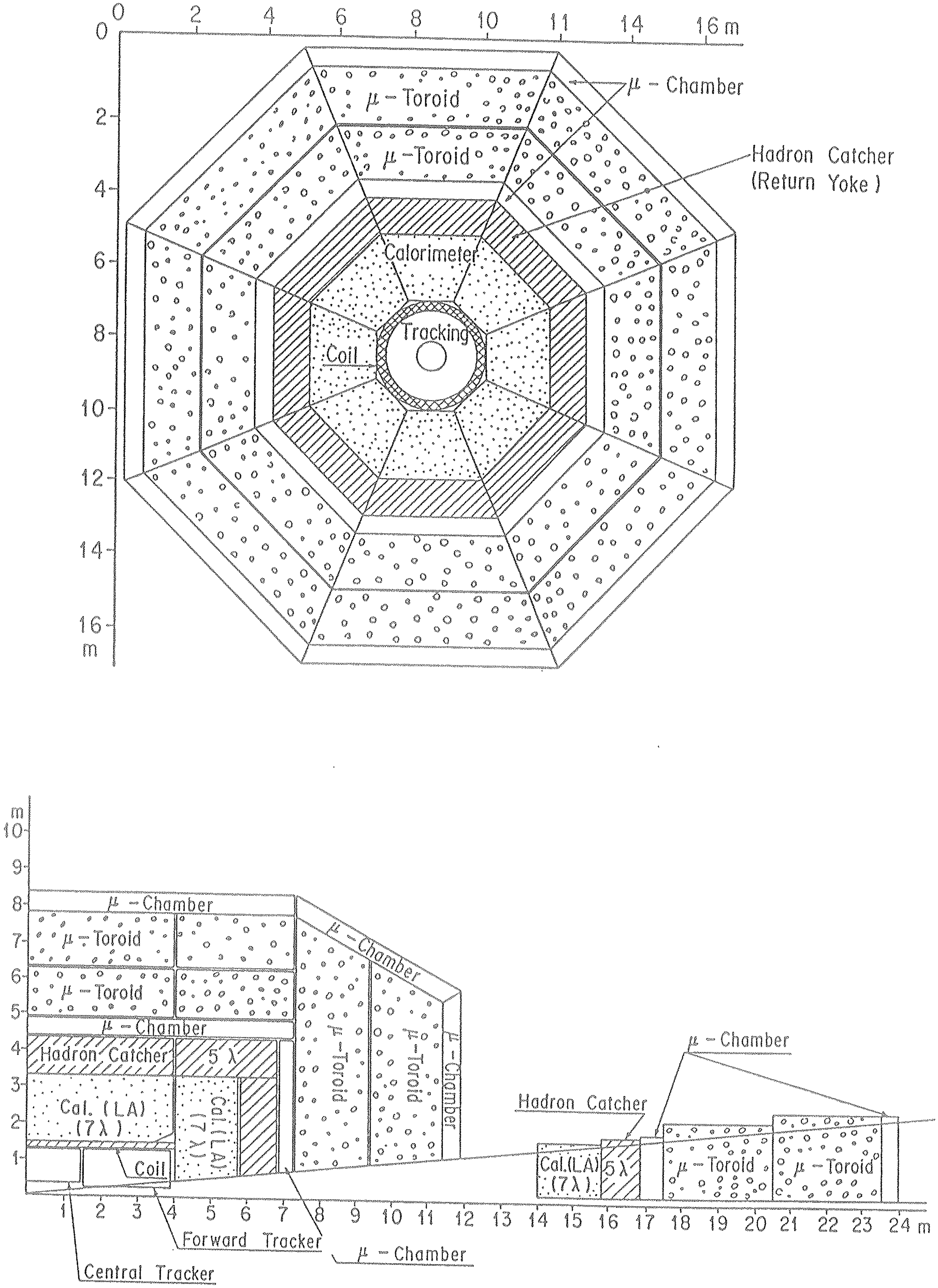

μ - Chamber
μ - Toroid
μ - Toroid
Hadron Catcher
(Return Yoke)
Calorimeter
Tracking
Coil
μ - Chamber
μ - Toroid
μ - Toroid
μ - Chamber
Hadron Catcher
5 λ
Cal. (LA)
(7 λ)
Cal. (LA)
(7 λ)
μ - Toroid
μ - Toroid
μ - Chamber
Coil
Hadron Catcher
Cal.(LA)
(7λ)
5λ
μ - Toroid
μ - Toroid
μ - Chamber
Forward Tracker
Central Tracker
μ - Chamber

Fig. 1

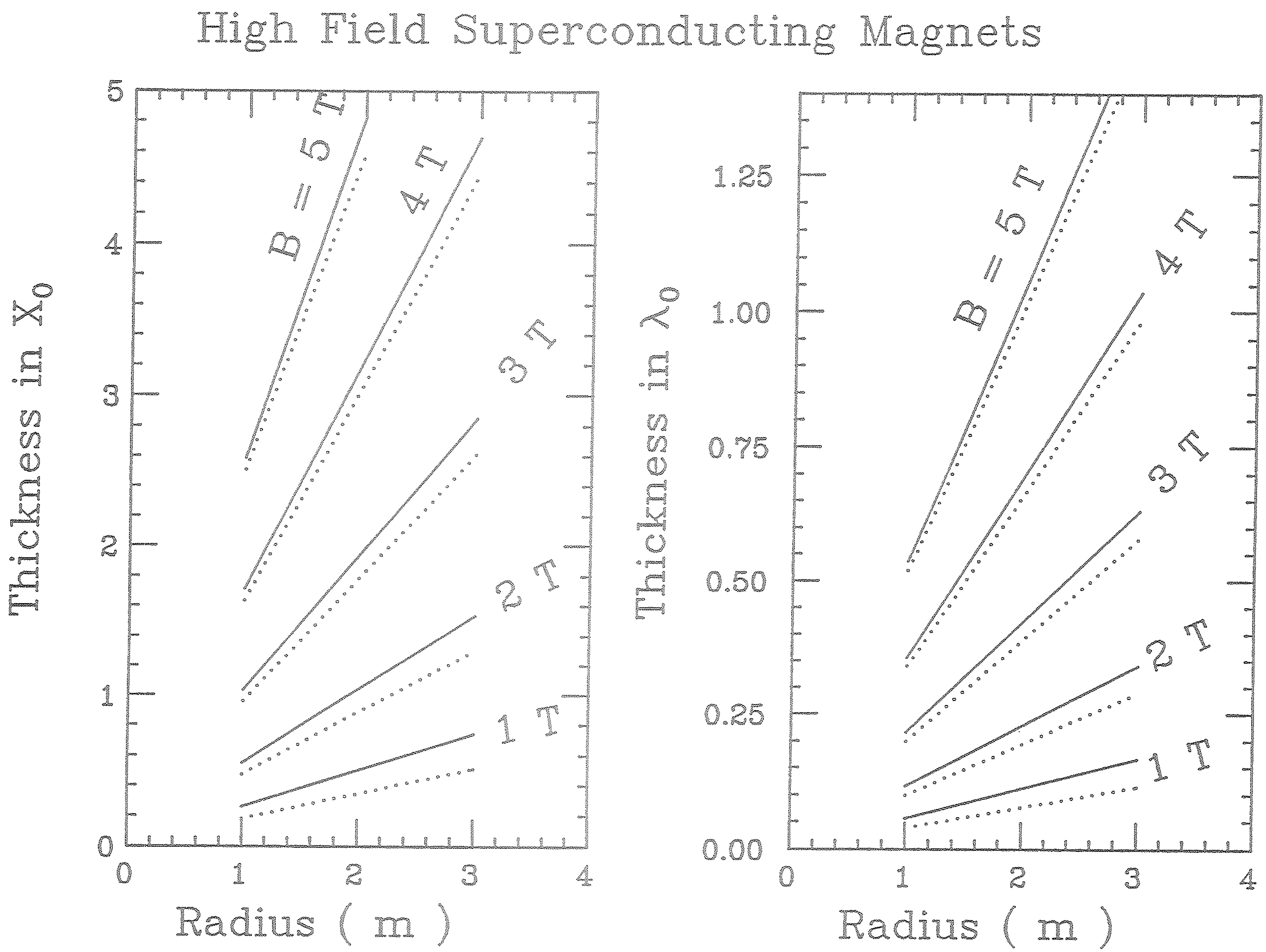
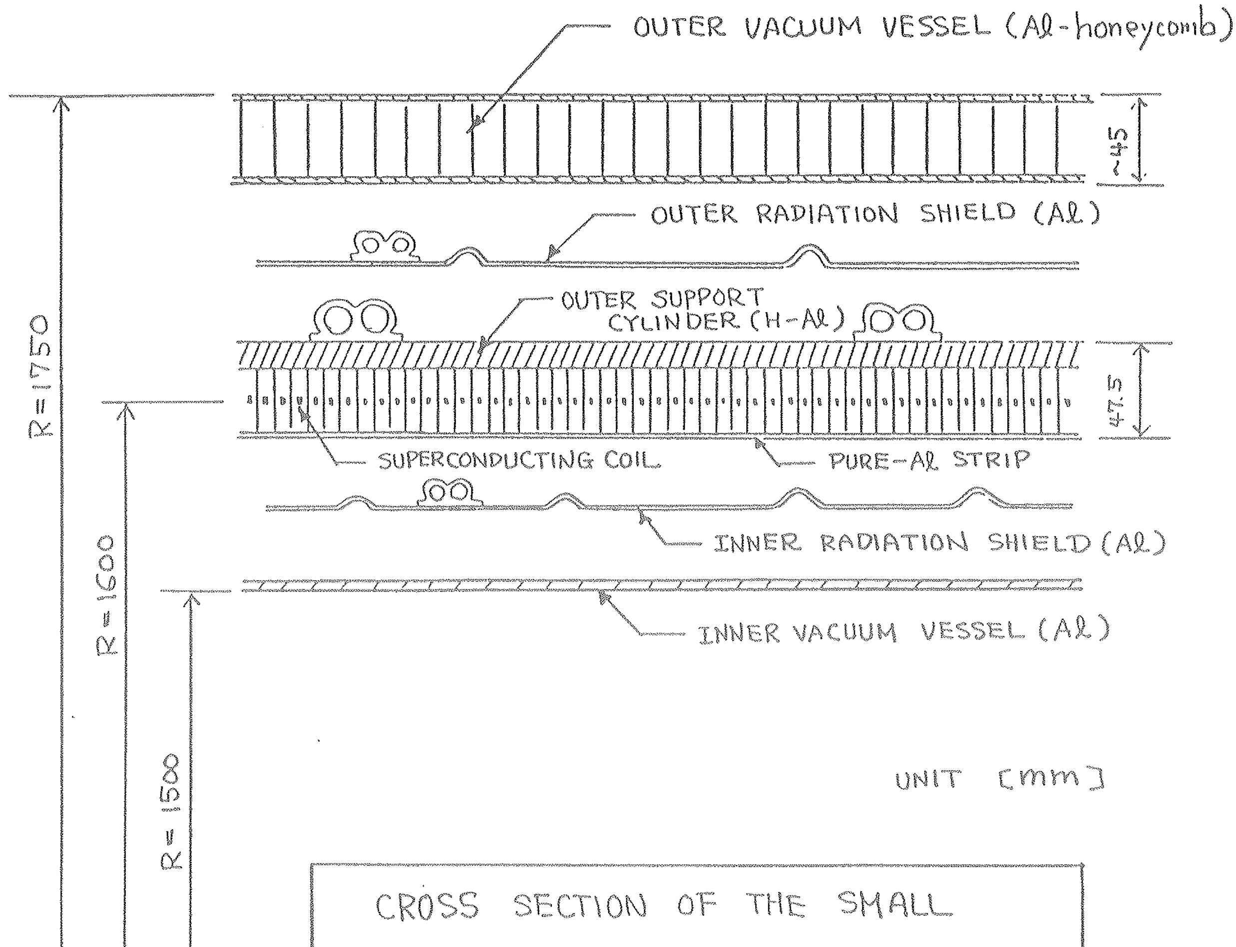
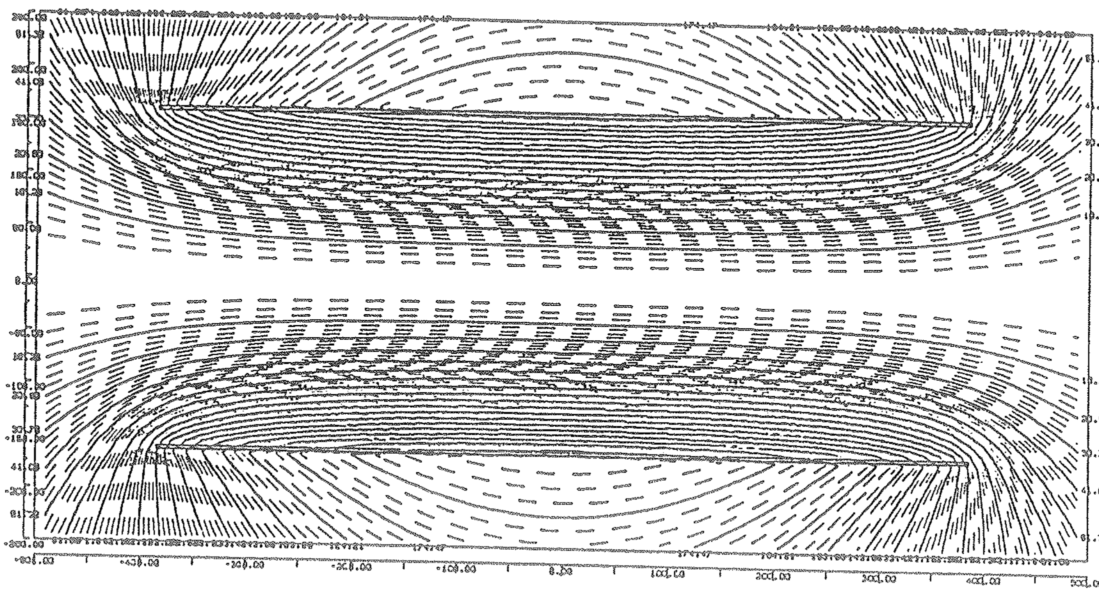

High Field Superconducting Magnets
Thickness in X_0
Radius (m)
B = 5 T
4 T
3 T
2 T
1 T
Thickness in λ_0
Radius (m)
B = 5 T
4 T
3 T
2 T
1 T

Fig. 2

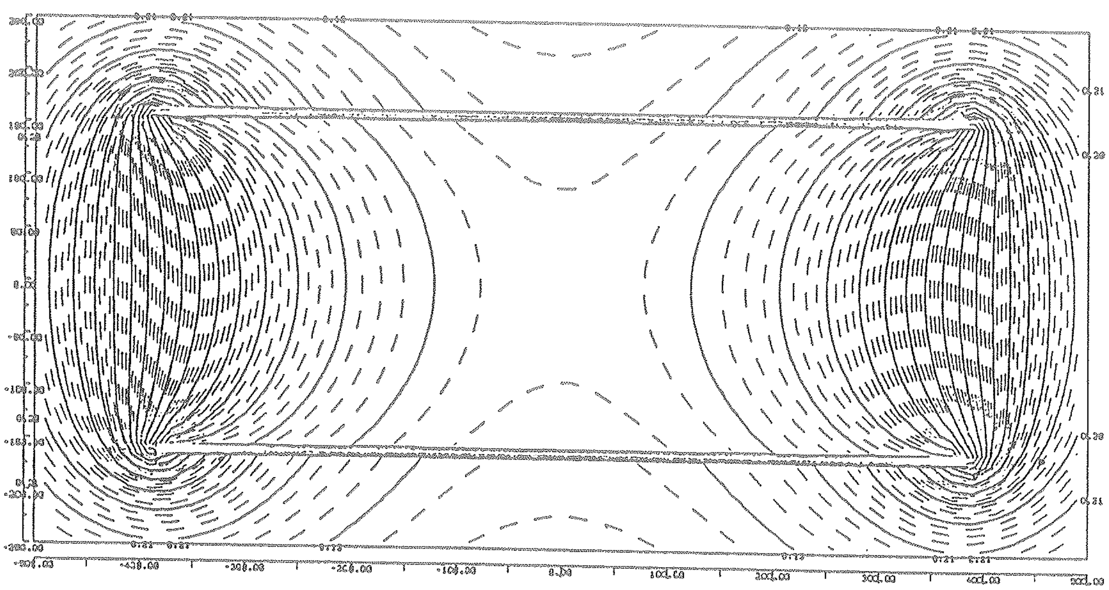


CROSS SECTION OF THE SMALL THIN SOLENOID AT B= 2T

Fig. 3



(a)



(b)

Fig. 4